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A SUMMARY REPORT OF MAJOR STUDIES UNDER THE  
PROGRAM "HIGH-SPEED HYDROFOIL STRUTS AND FOILS"

DAVID W. TAYLOR NAVAL SHIP  
RESEARCH AND DEVELOPMENT CENTER

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)  A three-year program was undertaken to determine the feasibility of developing a strut-foil system for high-speed operation that would also perform satisfactorily at takeoff and moderate speeds. Following identification of possible risk areas and design problems, the major objectives and approaches were established. The evaluation  (Continued on reverse side)		

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Task Area ZF 43 421 001  
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(Block 19 continued)

High-Speed Hydrofoil Craft  
Hydrofoil Maneuvering

(Block 20 continued)

included determination of representative hydrodynamic loads and a series of model tests in the areas of hydrodynamic efficiency, cavity stability, side force and ventilation envelop, and strut flutter.

The present study shows that a strut/foil system with a reasonably good high-speed operational capability can be designed that is also capable of performing efficiently at moderate speeds. Recommendations are made for additional theoretical and experimental studies in certain areas to further improve foil efficiency.

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## ADMINISTRATIVE INFORMATION

The direct laboratory funding project that constitutes the subject of this report was established by the Naval Material Command in September 1972. Funding was provided under Program Element 62754N, Task Area ZF 43 421 001, Work Unit 1-1500-001.

## INTRODUCTION

Success in the operation of moderate-speed hydrofoils at 40 to 50 knots (20.6 - 25.7 m/sec) provides a technical foundation for exploring the feasibility of hydrofoils for operation at high speeds. Struts and foils represent one of the most critical subsystems in such a development. In September 1972, the Naval Material Command (NAVMAT) requested the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) to undertake a three-year program to determine the feasibility of developing a strut-foil system for high-speed operation of hydrofoil craft.

The major design criteria associated with naval hydrofoils include payload, range of foilborne operation, seakeeping quality, maneuverability and control, and structural strength. The payload and foilborne range of a hydrofoil craft depend greatly on the transport efficiency (effective lift-to-drag ratio), the available fuel weight fraction, and the specific fuel consumption. Therefore, the lift-to-drag ratio  $L/D$  of strut/foil systems can provide a basis for estimating the payload and foilborne range. In fact this ratio at takeoff may govern the required power that must be installed in the craft. The  $L/D$  ratio of a strut/foil system is therefore considered the most critical parameter in this study. Nevertheless, the overall evaluation requires simultaneous consideration of the possible risk areas associated with seakeeping quality, maneuvering and control, and structural strength.

Experience indicates that it is extremely difficult to avoid cavitation on a subcavitating foil at a speed much above 50 knots (25.7 m/sec). Many institutes and laboratories have investigated two basic

approaches to high-speed strut and foil design. One involves the use of a fully wetted, base-vented section and the other a supercavitating section.<sup>1</sup> Typical section profiles of subcavitating (streamlined) base-vented, and supercavitating foils are given in Figure 1. The choice of one type over another requires tradeoffs among such aspects as hydrodynamic performance and structural strength at design speeds as well as mission requirements of the hydrofoil craft in various sea conditions. Foils with supercavitating sections and struts with fully wetted, base-vented sections were found to be the most desirable for operation at 80 knots (41.2 m/sec) and above. Since both types of sections are operated with cavity flows, the maximum hydrodynamic efficiency obtainable with these strut/foil systems may be inherently lower than conventional subcavitating strut/foil systems.

The major objectives in this program were:

1. To identify quantitatively the actual technical problems to be encountered and to introduce the new approaches to circumvent them.
2. To generate a data base for solving these problems and thus enable selection of a strut/foil system that can operate adequately throughout the whole designed speed range.
3. To recommend improvements in foil efficiency and indicate other areas requiring further theoretical and experimental studies.

The program was initiated in September 1972 and completed in June 1975. An appendix (included for information of the sponsors) indicates the milestones at various stages of the program (Tables 1-3) and the related allocations and expenditures (Table 4).

## DESIGN PROBLEMS

### FOIL EFFICIENCY

The payload and range of foilborne operation of a hydrofoil craft depend greatly on the hydrodynamic efficiency (L/D) of its strut/foil

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<sup>1</sup>Shen, Y.T. and R. Wermter, "Recent Studies of Struts and Foils for High-Speed Application," AIAA/SNAME Advanced Marine Vehicles Conference, Arlington, Va. (Sep 1976). A complete listing of references is given on page(s) 33-36.

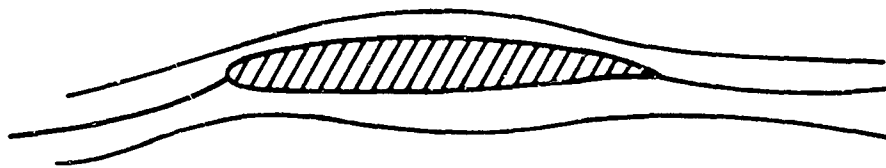


Figure 1a - Subcavitating Foil

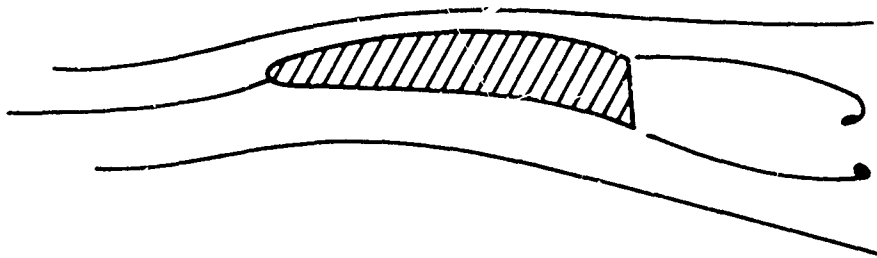


Figure 1b - Base-Vented Foil

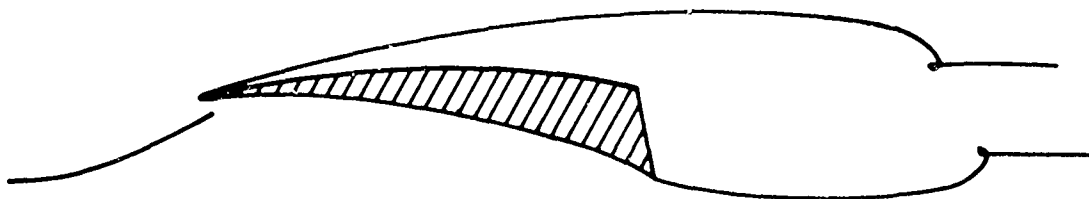


Figure 1c - Supercavitating Foil

Figure 1 - Typical Section Profiles of High-Speed Foils



system. It is recognized that high angles of attack are generally required to reliably generate a full cavity on a supercavitating foil. Unfortunately, the result is high cavity drag and low hydrodynamic efficiency. Accordingly the first priority in the study was assigned to improvement of foil efficiency.

In the past, remedial efforts have concentrated on the development of low drag supercavitating sections. Although a foil with a thinner section generally produces less cavity drag and higher hydrodynamic efficiency than does a thicker section, this improved hydrodynamic efficiency is achieved at the expense of lower structural strength. Thus a tradeoff between hydrodynamic efficiency and structural strength is required in the design of a supercavitating foil. Unfortunately, realistic representative hydrodynamic loads were not established for high-speed hydrofoils and there is still no well developed hydrodynamic design procedure for a three-dimensional supercavitating foil.<sup>2</sup>

The leading edge of a traditional supercavitating foil is usually sharp and thin to encourage the early development of full cavity on the foil and to minimize cavity drag. Unfortunately, high-speed tests both in towing tanks and water tunnels have shown foil vibration or leading edge flutter due to the thin leading edge.<sup>3</sup>

#### CAVITY STABILITY

Most theoretical and experimental studies in the 1960's were concerned with the smooth-water characteristics of supercavitating foils and little theoretical and experimental efforts were devoted to the unsteady and control aspects.<sup>4</sup>

A stable cavity is essential to the smooth operation of a supercavitating hydrofoil. One simple way to ventilate the foil cavity is to

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<sup>2</sup>Wang, D.P., "A Survey on Supercavitating Flow around Hydrofoils," prepared for NSRDC under Contract N00600-72-D-0306 (Jan 1973).

<sup>3</sup>Baker, E.S., "Review of Supercavitating Hydrofoil Experiments, 1955 through 1972," NSRDC Evaluation Report SPD-567-01 (Jul 1975).

<sup>4</sup>Conolly, A.C., "Unsteady and Control Aspects of Supercavitating and Superventilated Hydrofoils--A State of the Art Investigation," NSRDC Evaluation Report SPD-479-12 (Feb 1974).

introduce air from the free surface through the trailing cavity behind a blunt-based strut. However, strut choking (i.e., blocked air path from the free surface) on a supercavitating foil with a blunt-based strut section has been observed in high-speed model tests. This will result in an unpredictable lift force on the foil. Accordingly another critical design problem considered in the program was how to improve cavity stability or minimize the cavity pressure fluctuation in waves.

#### STRUT SIDE FORCE

The struts of a high-speed hydrofoil must provide adequate size, length, structural strength, and predictable side force characteristics with lowest resistance. In addition, the struts must provide a sufficient air path from the atmosphere to vent the foil if a superventilated condition is desired.

If the lateral force developed by a strut is not a smooth, single-valued function of yaw angle, the craft will be unable to maintain a steady turn and the stability of the craft on a straight course may be compromised. It has been shown experimentally that strut side ventilation is responsible for this erratic behavior of hydrofoils.<sup>5</sup> Information on strut side force and ventilation envelop at high speeds is thus another critical need in evaluating the maneuverability and controllability of a high-speed hydrofoil craft.

#### HYDROELASTIC STABILITY

Flutter problems (i.e., hydroelastic instability) played a very crucial role in the early stage of airplane development. Although flutter has not actually been experienced by existing hydrofoils; the question naturally arises as to whether it will be present in a high-speed hydrofoil (up to 80 knots, 41.2 m/sec). High-speed base-vented struts may be more susceptible to the hydroelastic problems of flutter

and divergence than are moderate-speed streamlined struts. The occurrence of flutter or divergence on the struts may lead to a catastrophic failure for the craft.<sup>5</sup>

#### OPERATIONAL EFFICIENCY FOR A WIDE RANGE OF SPEEDS

The capability to operate efficiently at moderate speeds (40-50 knots) may be equally as important in the design of a high-speed hydrofoil craft as the actual operational capability at high speeds. Unfortunately, the supercavitating foils that enable hydrofoils to operate at high speeds make for very inefficient operation at moderate speeds. The difficulty stems from the different requirements on lift coefficient  $C_L$  at moderate and at high speeds. The increase in the drag coefficient ( $C_D$ ) of a supercavitating foil is generally much higher than that of the lift coefficient  $C_L$  and will result in poor hydrodynamic efficiency at off-design operation. The consequence is a great reduction in the available range of foilborne operation.

A successful takeoff must be achieved before a hydrofoil can begin to operate in the foilborne condition. When a supercavitating foil is employed, then at takeoff the drag penalty is very severe and the propulsive efficiency is likely to be low. If the drag is too large, there may be inadequate thrust to accelerate the craft. Thus the ability of a strut/foil system designed for high-speed operation to perform satisfactorily on takeoff at 35 knots (18.0 m/sec) has long been considered a major goal.

#### APPROACH

A data base for the design of strut/foil systems can be generated through a series of theoretical and/or experimental studies. The approach established for this program emphasized experimental studies but consideration was also given to adequate theoretical support.

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<sup>5</sup>Rood, Jr. E. and N. Dailey, "Catastrophic Hydroelastic and Side Ventilation Phenomena on High-Speed Hydrofoil Struts," NSRDC Evaluation Report SPD-479-10 (Mar 1973).

A single fully submerged foil was considered. Although the maximum craft design speed was assumed to be 80 knots, it was felt that the data obtained in this program should be equally applicable to higher speeds. A takeoff speed of 35 knots was assumed. The possible interference effects from propulsive devices or other strut/foil systems were not considered.

After a literature review of all hydrodynamic aspects of the problem (available theoretical and experimental results, applicable control principles, and hydroelastic studies), it was decided to design and evaluate an experimental system while simultaneously extending theories to assist in future designs. Existing strut/foil systems were utilized in experimental studies to assess the boundaries of the problems. -18\*

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<sup>6</sup>Ravenscroft, L.T., "First-Order Foilborne Range Estimated for High-Speed Hydrofoils," NSRDC Evaluation Report SPD-479-09 (Feb 1973).

<sup>7</sup>Shen, Y.T., "Nonlinear Theory for Supercavitating Hydrofoil of Finite Span near a Free Surface," Cal. Inst. Technol. report prepared under Contract N00014-67-A-0094-0023 (Jul 1973).

<sup>8</sup>Holling, H.D., "Experiments of Two Single-Strut Hydrofoils," NSRDC Evaluation Report SPD-575-01 (Nov 1974).

<sup>9</sup>Dailey, N., "Experimental Investigation of the Ventilation Force Characteristic of One NACA-16 and Two Blunt-Based Parabolic Surface-Piercing Struts," NSRDC Evaluation Report SPD-479-H-07 (Nov 1973).

<sup>10</sup>Dailey, N., "Determination of Selected Strut Force and Ventilation Characteristics Using the Rotating Arm Facility," NSRDC Evaluation Report SPD-479-H-06 (Nov 1973).

<sup>11</sup>Rood, Jr. E., "An Empirical Mathematical Model of the Hydrodynamics for the FRESH-1 Hydrofoil Systems," NSRDC Evaluation Report SPD-479-11 (Dec 1973).

<sup>12</sup>Owings, R. and M. Rathbun, "Final Report of Work Performed under Contract N00167-73-C-0244 (Mathematical Model for Dynamic Simulation)," (Aug 1973).

<sup>13</sup>Bruce, E.P., "A Parametric Study of Four-Bar Linkages Designed to Produce Sinusoidal Angle-of-Attack Variations with Minimal Linear Displacement," Penn. State Univ. ARL TM 73-144 (Jun 1973).

<sup>14</sup>Parkin, B.R., "Fully Cavitating Hydrofoil Response to Streamwise Sinusoidal and Sharp-Edged Gusts at Zero Cavitation Number," Penn State Univ, ARL TM 74-172 (Jun 1974).

\*References 15-18 continued on next page.

A practical supercavitating foil must be able to sustain any possible hydrodynamic loads encountered during its service life. The first priority then was to establish representative hydrodynamic loads for structural design. The limit load approach presently employed for Navy subcavitating hydrofoil ship design is adopted for the present study. The critical loading conditions anticipated in service are specified and detailed loads are calculated corresponding to each of the loading conditions.

Extensive studies on this subject were carried out by Hoyt, Ma, Buckley, and Ryland.<sup>19</sup> The representative hydrodynamic loads so developed were then used to evaluate the feasibility of constructing a system with a foil of supercavitating section and struts with blunt-based parabolic profiles (see Figures 2 and 3). Arbitrarily designated as TAP-1, the system was intended to support a 200-ton hydrofoil.

The conceptual design was limited to (1) structural design of the foil, (2) foil to strut connection, (3) the flap and its actuation system, and (4) the sizing of the king post. The criterion for maximum allowable stress in any member was based on the use of HY-130 steel or,

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<sup>15</sup>The Garfield Thomas Water Tunnel Staff, "Progress Report for FY73-74 for the NSRDC/ARL Cooperative Hydrofoil Research Program," Penn. State Univ, ARL TM. 74-235 (Aug 1974).

<sup>16</sup>Barker, S.J. et al., "Experiments on a Cavitating Hydrofoil Fitted with Flaps in Two- and Three-Dimensional Flow," GALCIT Report HSWT-1120 CIT (May 1975).

<sup>17</sup>Wang, D.P., "Brief Summary of the Foil Design for High-Speed Hydrofoil Craft," prepared for NSRDC under Contract N00600-72-D-306-FD14-AL (1973).

<sup>18</sup>Besch, P.K. and E.P. Rood, Jr., "A Parametric Survey of Hydrofoil Strut Flutter," NSRDC Report 76-0050 (Mar 1976).\*

<sup>19</sup>Hoyt, E.D. et al., "Structural Design Study of TAP-1 Supercavitating Foil and Struts," NSRDC Report 4705 (Aug 1975).

\*Partially supported by this program.



Figure 2 - TAP-1 Model

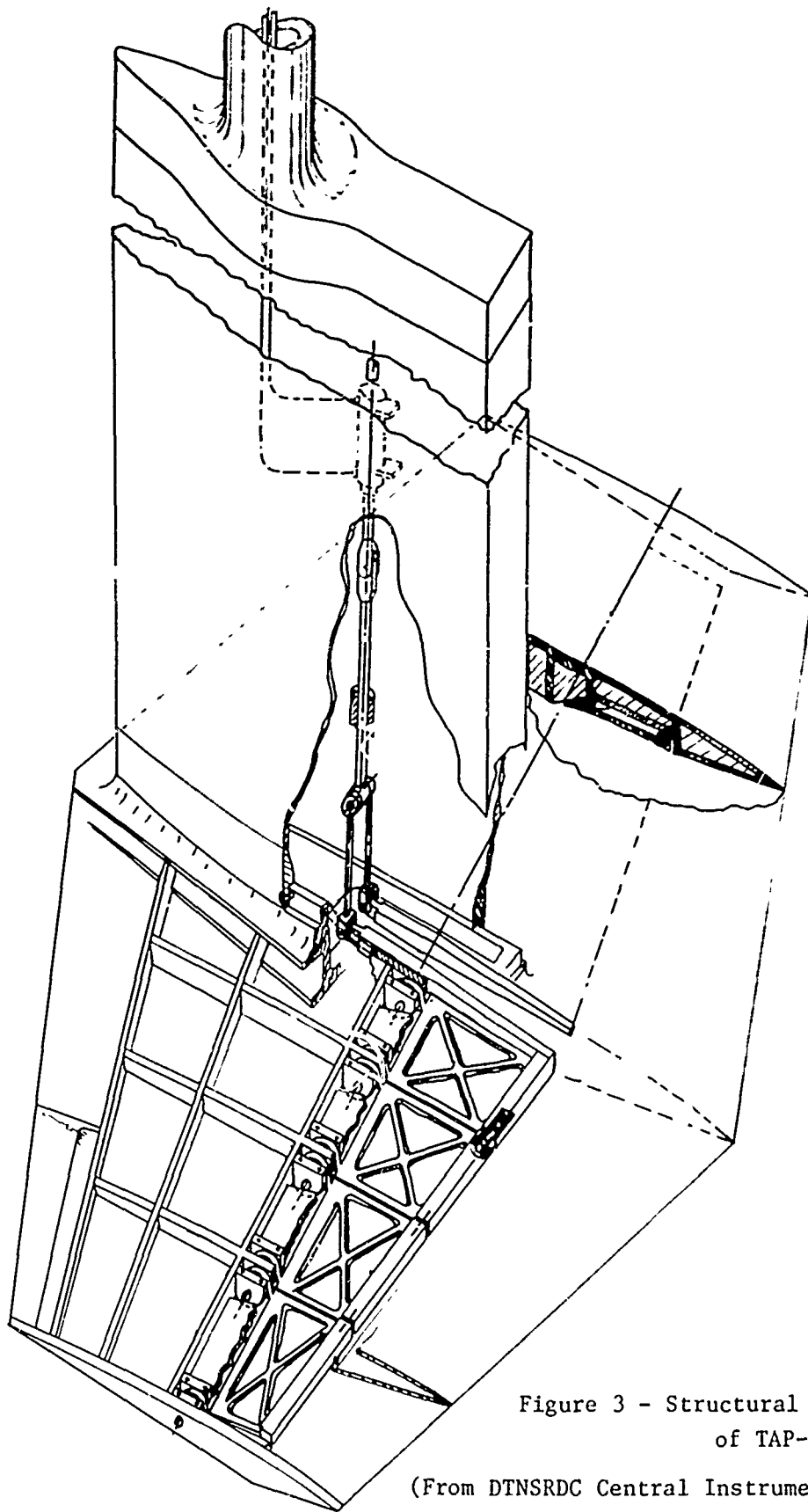


Figure 3 - Structural Design Concept  
of TAP-1 Hydrofoil

(From DTNSRDC Central Instrumentation Department)

alternatively, precipitation-hardened 17-4 PH stainless steel. An investigation by the Central Instrumentation Department at DTNSRDC indicated that the design was structurally adequate to withstand the anticipated critical loads.\*

In concurrent major efforts, cavity stability in waves and strut flutter were studied.<sup>20-30</sup> A kinematically scaled TAP flutter model was

<sup>20</sup>Wermter, R. and Y.T. Shen, "A High-Speed Hydrofoil Strut and Foil Study," AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, California (Feb 1974).

<sup>21</sup>Dobay, G. and E.S. Baker, "Special Problems in the Design of Supercavitating Hydrofoils," AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, California (Feb 1974).

<sup>22</sup>Baker, E.S., "Notes on the Design of Two Supercavitating Hydrofoils," NSRDC Evaluation Report SPD-479-13 (Jul 1975).

<sup>23</sup>Holling, H. et al., "Experimental Evaluation of the Performance of the TAP-1 Supercavitating Hydrofoil Model at 80 Knots," NSRDC Report 4681 (Jul 1975).

<sup>24</sup>Holling, H.D., "Takeoff Experiments for a Newly Designed High-Speed Supercavitating Hydrofoil (TAP- )," NSRDC Evaluation Report SPD-575-02 (Apr 1975).

<sup>25</sup>Gregory, D.L., "Preliminary Propulsion Performance Estimates for an 80-Knot Hydrofoil Craft," NSRDC Evaluation Report SPD-606-01 (Jun 1975).

<sup>26</sup>Wang, D.P. and Y.T. Shen, "A Validation Study of the Mixed Foil Concept for High-Speed Hydrofoils," Penn. State Univ. ARL TM 75-171 (Jun 1975). (also to be published in the Journal of Ship Research, June 1976)

<sup>27</sup>Stahl, R. and E.E. Zarnick, "The Mean and Oscillatory Forces on a Hydrofoil with Combined Natural and Forced Ventilation from Experiments in Regular Waves," NSRDC Evaluation Report SPD-626-01 (May 1975).

<sup>28</sup>Shen, Y.T., "General Scaling Problems on Fully Cavitating and Ventilated Flows," 17th American Towing Tank Conference, Cal. Inst. Technol. (Jun 1974).

<sup>29</sup>Besch, P.K. and Y.-N. Liu, "Hydroelastic Design of Subcavitating and Cavitating Hydrofoil Strut Systems," NSRDC Report 4257 (Apr 1974).\*\*

<sup>30</sup>Rood, E., "Estimated Hydrodynamic Strut Side Forces on a 200-Ton, 80-Knot Hydrofoil Craft," NSRDC Evaluation Report SPD-584-01 (Oct 1974).

\* Reported informally by A.P. Clark as NSRDC Technical Note CID 29-48.

\*\* Partially supported by this program.



developed. And a six-degree-of-freedom mathematical model was employed to evaluate the maneuvering characteristics of a high-speed hydrofoil craft equipped with a TAP-1/foil/strut system.

The performance of the TAP-1 foil during high-speed cruising was found to be similar to that of the BuShips parent foil,<sup>3</sup> but performance at takeoff and at moderate speeds was considered inadequate. It had been recognized that large cavity drag would probably degrade performance at takeoff and moderate-speed operation and thus penalize payload and/or foilborne range. Accordingly, a new design concept for high-speed application was simultaneously explored. This resulted in a mixed foil and pseudoblunt-based strut system; see Figure 4 for details. Theoretical validation of this "mixed foil" concept was encouraging. These results, together with the knowledge gained from the TAP-1 studies, led to the development of an improved strut-foil system designated as TAP-2.

It had been hoped originally that the candidate strut/foil system which evolved from the program could actually be demonstrated on an existing craft such as FRESH-1. However, funding limitations soon caused retrenchment of these plans, and the feasibility study utilized a series of model tests in a variety of hydrodynamic facilities to increase understanding of the scaling laws for full-scale prediction. The major efforts conducted in this time period are indicated in References 31-40.\*

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<sup>31</sup>Nelka, J.J., "Effect of Mid-Chord Flaps on the Ventilation and Force Characteristics of a Surface-Piercing Hydrofoil Strut," NSRDC Report 4508 (Aug 1974).

<sup>32</sup>Baker, E.S., "Design of Hydrofoil Model TAP-2," NSRDC Evaluation Report SPD-575-03 (Jun 1975).

<sup>33</sup>Kramer, R.L., "Performance of the NSRDC TAP-1 and TAP-2 Hydrofoil Model-Lockheed Missiles & Space Co. Inc., TM 5724-75-46 (May 1975).

<sup>34</sup>Holling, H., "Takeoff Experiments of a High-Speed Hydrofoil System (TAP-2)," NSRDC Evaluation Report SPD-575-04 (Jun 1975).

<sup>35</sup>Wang, D.P. and Y.T. Shen, "A Theory for High-Speed Hydrofoils," NSRDC Evaluation Report SPD-479-14 (Jun 1975).

\* References 36-40 continued on next page.

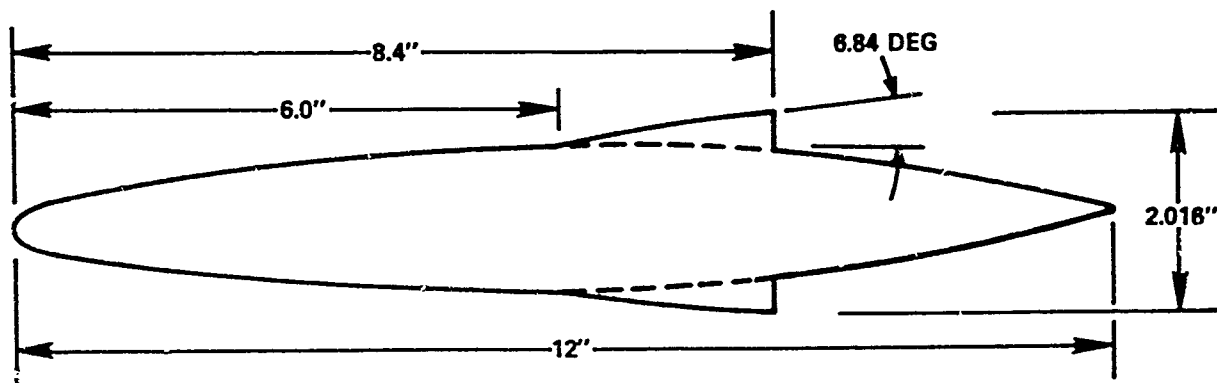


Figure 4a - Pseudoblunt-Based Strut

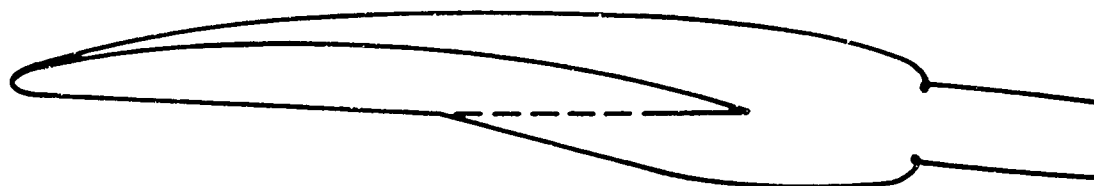


Figure 4b - Mixed Foil

Figure 4 - The New Design Concept of Mixed Foil

## MAJOR STUDIES

### DEVELOPMENT OF STRUT/FOIL SYSTEM

The major objectives of this effort were (1) to evaluate the current hydrodynamic design procedure and to design a supercavitating foil to achieve the highest L/D ratio obtainable at high-speed cruising conditions, (2) to demonstrate the feasibility of achieving takeoff at 35 knots, (3) to investigate the possible leading edge vibration problem at full-scale speeds, (4) to determine cavity pressure versus craft speeds for cavity stability studies, and (5) to generate a data base on side force characteristics of parabolic and pseudoblunt-based struts fitted to supercavitating foils.

Following extensive tradeoff studies between hydrodynamic efficiency and structural strength of supercavitating sections,<sup>21</sup> the foil designated as TAP-1 was designed by using a nonlinear cavity flow theory for section shapes. The foil sections were then twisted in the spanwise direction of the planform with techniques reported in detail by Baker.<sup>22</sup>

A base-vented parabolic strut was selected for the TAP-1 foil as the parent section. This type of strut has been extensively used in past high-speed hydrofoil programs. Two strut thickness to chord ratios of 12 and 18 percent and strut spray wedges were selected to investigate

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<sup>36</sup>Parkin, B.R. et al., "A Numerical Design Study of Fully Cavitating Hydrofoil Sections Having Prescribed Pressure Distributions," Penn. State Univ. ARL TM 75-170 (Jun 1975).

<sup>37</sup>Yim, B., "Theory of Ventilating or Cavitating Flow about Symmetric Surface-Piercing Struts," NSRDC Report 4616 (Sep 1975).

<sup>38</sup>Rood, Jr. E.P., "Turning Maneuver Limitations Imposed by Sudden Strut Side Ventilation on a 200-Ton, 80-Knot Hydrofoil Craft," NSRDC Evaluation Report SPD-584-02 (May 1975).

<sup>39</sup>Rothblum, R.S., "Feasibility of Boundary-Layer Control by Tangential Blowing for Suppression of Side Ventilation on Base-Vented Hydrofoil Struts," NSRDC Evaluation Report SPD-625-01 (Jun 1975).

<sup>40</sup>Besch, P.K., "Flutter Investigation of a High-Speed Hydrofoil Strut and Foil System," NSRDC Evaluation Report SPD-584-03 (Jun 1975).

the effects of strut profiles on foil performance and extent of ventilation in the foil cavities. The assembly of this strut/foil system is given in Figure 2.

The TAP-1 strut/foil system was first tested in the Aircraft Landing Dynamics Facility at NASA to determine its high-speed performance up to a speed of 92 knots (47.3 m/sec). The maximum L/D measured in full cavity flow at one chord submergence was 6.6.<sup>23</sup> This value is similar to the value obtained by using the BuShips parent foil. No vortex shedding or leading edge vibration was observed. However, there were differences between the test results and the design predictions of foil performance.

The effectiveness of flap for unsteady load control had been well demonstrated in existing naval hydrofoil craft. It had also been observed that a flap can be used effectively as a high-lift device. Accordingly, takeoff experiments on the TAP-1 system were carried out to determine the most favorable combination of flap angle and incidence angle for takeoff. The experiments were conducted at Langley Tank 1 by Holling.<sup>24</sup> The maximum L/D obtainable at the design takeoff lift was around 3 to 4.

For a given craft weight and L/D ratio, Gregory<sup>25</sup> estimated the required shaft horsepower, propeller diameter, and rpm at both craft speeds of 35 and 80 knots using controllable pitch propellers. Empirical formulas to estimate the weight components of naval hydrofoil are given by Ravenscroft.<sup>6</sup> Based on the estimated available shaft horsepower, the minimum overall system L/D ratio at takeoff--including the aerodynamic drag and propulsive drag--was calculated at around 6. The TAP-1 strut/foil system did not satisfy this criterion.

The performance of a subcavitating foil on naval hydrofoils equipped with streamlined foils and struts had already been demonstrated at speeds up to 50 knots. It had also been observed that takeoff speeds in the neighborhood of 30 knots was not a problem for present-day, moderate-speed hydrofoils. The L/D ratios of such a moderate-speed hydrofoil are generally 10 to 12 at takeoff and greater than 15 in the foilborne condition. To circumvent the takeoff problem as observed in the TAP-1

foil and to increase the range of foilborne operation, it indeed becomes desirable for a high-speed hydrofoil to have the capability to cruise at moderate speeds and take-off in subcavitating modes efficiently.

To achieve that goal, a new design concept was introduced--the mixed foil and pseudoblunt-based strut. A mixed foil is a streamlined hydrofoil equipped with a flap or other device which can be activated above a certain speed to change the flow around the foil into a supercavitating flow. At takeoff and at moderate speeds, a mixed foil is operated as a subcavitating foil; at high speeds, it is operated as a supercavitating foil. A pseudoblunt-based strut is a streamlined strut equipped with a flap or other devices which can be activated above a certain speed to become a base-vented strut. Sketches of this mixed foil and pseudoblunt-based strut are given in Figure 4.

Based on a series of two-dimensional tests, a hydrodynamic validation study of the concept of the mixed foil was carried out theoretically on two hydrofoils of planoconvex sections and a pseudoblunt-based strut. The L/D ratio of this strut/foil system was found to be around 13 to 14 at takeoff and about 18 at moderate cruising speeds. At high-speed cruising (80 knots), the foil was operated in a supercavitating condition with an L/D ratio of 7.6.

These results suggest that a reasonably good L/D ratio can be achieved at high-speed cruising and that the hydrodynamic efficiency of a mixed foil at moderate-speed cruising is similar to that of existing hydrofoils.

This new concept and the knowledge gained from the TAP-1 foil studies were utilized in the design of the strut/foil system designated as TAP-2. The TAP-2 foil was designed with a small leading edge radius and the strut section was an NACA 16-012 profile fitted with two types of midchord flaps. The TAP-2 model strut/foil assembly is shown in Figure 5.

A series of simulated high-speed experiments was conducted at Lockheed Underwater Missile Facility, a controlled atmosphere towing

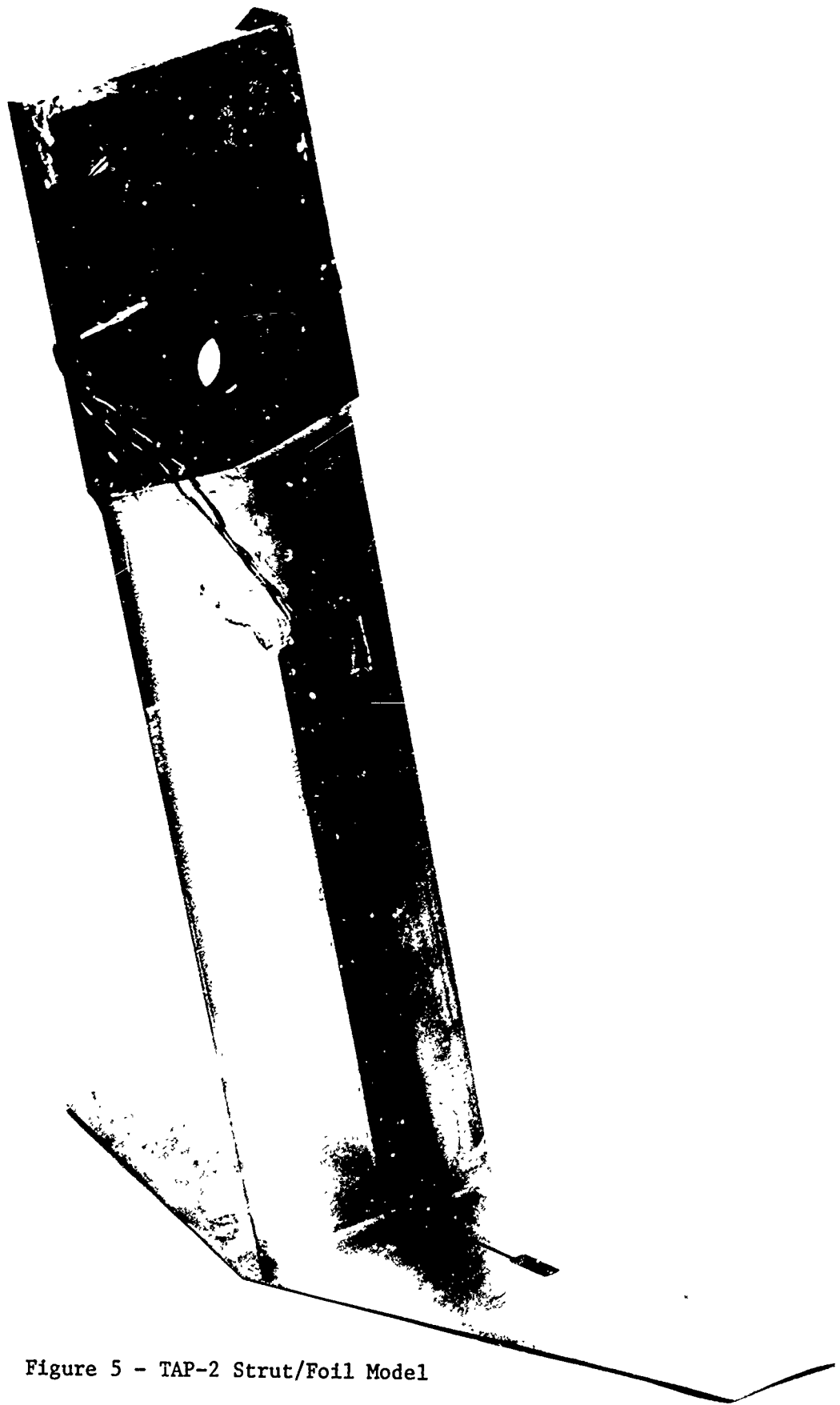


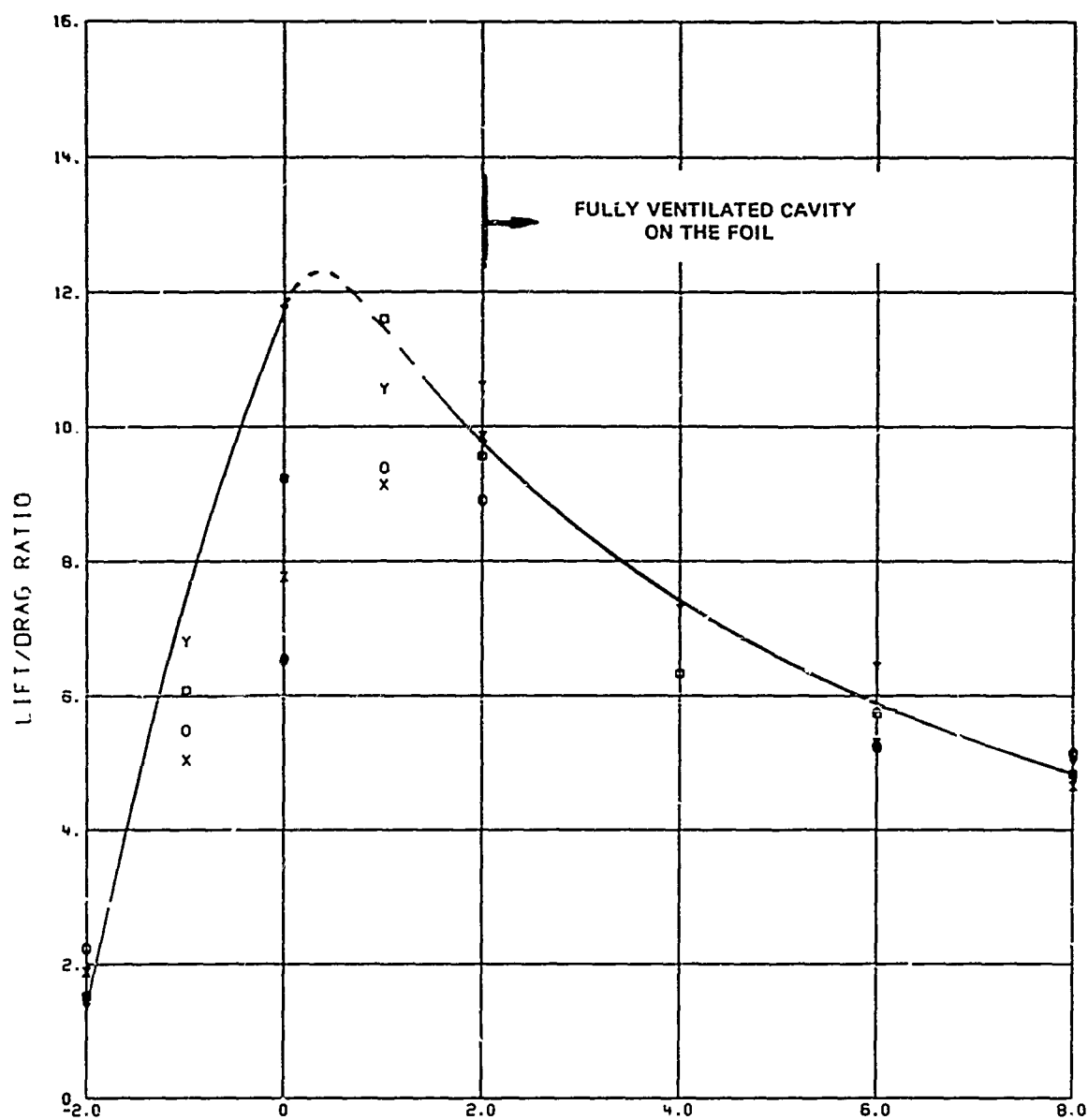
Figure 5 - TAP-2 Strut/Foil Model

tank.<sup>33</sup> The model was tested under simultaneous cavitation and Froude scale conditions. At high-speeds, the foil was designed to operate in a supercavitating condition. The maximum L/D ratio for the TAP-2 foil measured in full cavity flow at one chord submergence was approximately 9 to 10. Recall that the maximum L/D ratio for TAP-1 in full cavity flow was only 6.6. However, since the structural rigidity and the camber of the TAP-2 foil are not exactly the same as that of the TAP-1, a direct comparison of their hydrodynamic performance may not be exactly proper. Nevertheless the results obtained from the TAP-2 strut/foil system is encouraging. Figure 6 indicated the effect of pitch angle on TAP-2 foil performance for a model scale ratio  $\lambda = 1/15$ .

A series of takeoff studies on TAP-2 was carried out in the DTNSRDC towing tank by Holling.<sup>34</sup> At the takeoff speed of 35 knots and foil submergences of  $d/c = 2.0$  and  $3.0$ , the maximum measured L/D of the strut/foil system was 14.25, as shown in Figure 7. The L/D corresponding to the required lift coefficient was 12 to 14. This value is the same as that obtained in the mixed-foil validation study. Consequently, successful takeoff with the TAP-2 strut/foil system can be anticipated.

The hydrodynamic performance of TAP-2 at 45 knots was somewhat degraded because of cavitation and base ventilation on the foil. This drawback is attributed to improper design of the upper surface of the foil due to the lack of adequate theoretical tools. A mixed-foil design theory was subsequently developed by Wang and Shen.<sup>35</sup>

If the propulsive efficiency and the aerodynamic drag of a vehicle are known, the payload and foilborne range of a hydrofoil can be determined from the L/D ratio of the strut/foil system. Theoretical studies on mixed foils and experimental investigations on TAP-2 suggest that a high-speed hydrofoil equipped with mixed foils and pseudoblunt-based struts can be designed to operate efficiently at moderate speed and an efficient high-speed dash capability.



FOIL ANGLE OF ATTACK $\alpha$					
SPRAY WEDGE	A	FULL SCALE	SYM	FULL SCALE	SYM
RETA (DEG)	0.00	SPEED (KNOTS)		SPEED (KNOTS)	
D/C	1.0	50	0	70	○
SCALE	1/15	60	X	80	Y

Figure 6 - Hydrodynamic Characteristics of TAP-2 Foil  
(From Kramer<sup>33</sup>)



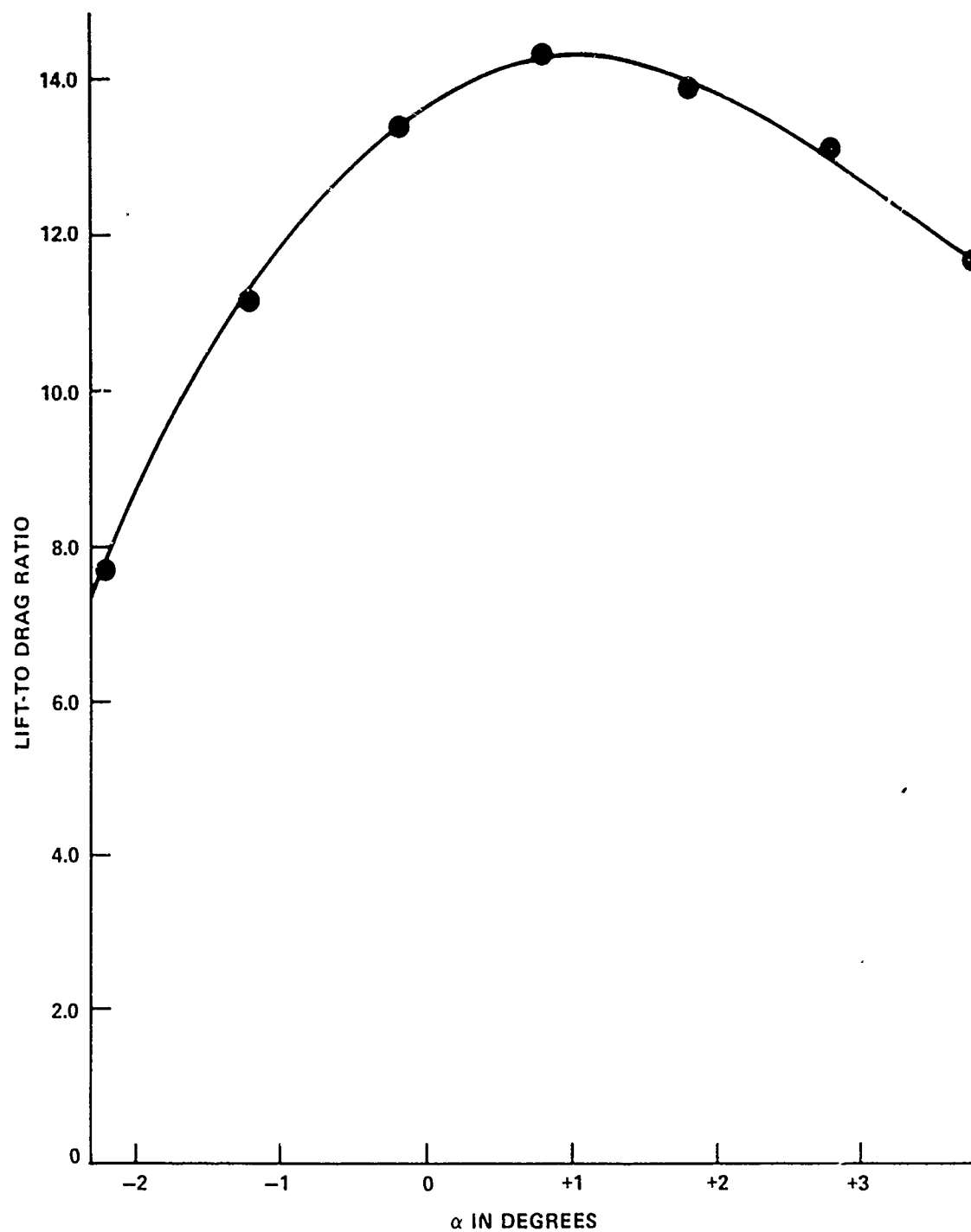


Figure 7 - Lift-to-Drag Ratio of TAP-2 System as a Function of Foil Incidence Angle for Speed of 35 Knots at  $d/c = 3.0$

## DEVELOPMENT OF STRUT AND FOIL DESIGN METHODS

Although the major effort in this project was experimentally oriented, some parallel theoretical effort was made in support of the experimental work.

### Supercavitating Section Design Method

Possible hydrodynamic trends for use in tradeoff studies for the preliminary design of fully cavitating hydrofoil sections were theoretically investigated. Hydrodynamic data were obtained from inverse calculations based on two-dimensional linearized cavity-flow theory. Supplementary data were also calculated from the direct problem of linearized cavity-flow theory in order to show off-design performance trends and to assess the effects of cavity-foil interference on the operating range of selected profiles. Results have been published on a parametric study of the effects of design cavitation number, lift coefficient, cavity thickness, and pressure distribution shape on hydrofoil section performance and geometry.<sup>36</sup>

### Three-Dimensional Supercavitating Foil Design Program

Yim represented the cavitating foil with a blunt-based strut beneath a free surface by a combination of vortex and source distributions. The integral equation for the unknown source distributions is solved numerically with a specified pressure distribution. The pressure is integrated on the foil for the cavity drag. The present theory attempts to incorporate the strut downwash and the free-surface corrections into an arbitrary three-dimensional supercavitating planform. The theoretical portion has been completed but further efforts are needed to finish the numerical calculation.

### Mixed-Foil Study

As already indicated, the cavity drag of a supercavitating foil at takeoff and moderate-speed operation is quite high because of the high angles of attack required to generate a sufficient  $C_L$ . On the other hand, a streamlined foil has been operated successfully up to 50 knots. A feasibility study was therefore undertaken to investigate the possibility of designing a foil that could be operated in the streamlined condition up to moderate speeds and then converted to a superventilated condition at higher speeds.<sup>26</sup> A linearized theory was developed for two-dimensional foils in an unbounded fluid. The lower surface profile is specified in terms of high-speed superventilating mode performance and the upper surface pressure distribution is specified in terms of sea-state requirements for moderate speeds.<sup>35</sup>

### Unsteady Supercavitating Flow Theory

A theory has been developed for determining the response of a hydrofoil to streamwise sinusoidal and sharp-edged gusts at zero cavitation number.<sup>14</sup>

### Three-Dimensional Theories for Surface-Piercing Struts

Flows of ventilating or cavitating struts have been analyzed numerically by using a three-dimensional mathematical model. The strut drag and the possible interference effect of a strut on the foil performance (strut downwash effect) have been computed. Further improvement in the foil design may be realized by incorporating this strut downwash effect.<sup>37</sup>

### STRUT SIDE FORCE AND VENTILATION STUDIES

Experiments on two parabolic struts with thickness of 12 and 18 percent and strut spray wedges were conducted in the NASA high speed-tank by Hollings, Baker, and Rood.<sup>23</sup> The struts were tested with the TAP-1 supercavitating foil. Significant parameters which affect the

ventilation inception angle and the side force slope for base-vented parabolic struts at high speeds were identified in this study. This set of data is very useful for evaluating maneuvering and control characteristics and for providing the loading in the vicinity of strut ventilation inception which may govern the structural loading criteria.

For the foil operated at a one-chord submergence, the experimental ventilation inception angles of parabolic struts at 80 knots were found to be around 3.25 and 2.5 deg for the foil in the ventilated and wetted conditions, respectively. This small range of allowable yaw angles at 80 knots raised concern about possible limitations on maneuvering characteristics of a high-speed hydrofoil.

A series of experiments on the pseudoblunt-based strut fitted with the TAP-2 supercavitating foil was carried out in the Lockheed controlled pressure towing tank at simulated full-scale craft speeds of 50 to 80 knots. With the foil operating at one chord submergence, the ventilation angle measured on the TAP-2 pseudoblunt-based strut at 80 knots was approximately 4.5 to 5 deg for the foils in the ventilated condition.<sup>33</sup> Recall that the ventilation angle measured on the TAP-1 base-vented parabolic strut was only 3.25 deg. Thus a significant improvement in ventilation sideslip angle was achieved by the TAP-2 pseudoblunt-based strut. These results suggest that greater maneuvering capability at high speeds may be realized with this new pseudoblunt-based strut than is possible with the traditional parabolic strut.

Within the range of tests, the measured side force slope of the TAP-2 strut was found to be almost twice that of the TAP-1 strut. This result suggests that greater controllability at high speeds may be achievable with this new pseudoblunt-based strut than with the traditional parabolic strut.

#### MANEUVERING STUDIES

Turning characteristics for an 80-knot hydrofoil in coordinated turns were predicted by Rood<sup>38</sup> using an existing six-degree-of-freedom computerized simulation. The automatic control system was the one used

in the FRESH-1 80-knot craft with some modification to the gains. It was concluded that an 80-knot, 200-ton hydrofoil with deeply submerged foils can be designed to perform coordinated turns with roll angles up to 15 degrees without suffering strut side ventilation; this corresponds to turning rates of 3.6 to 4.8 deg/sec and turning diameters of 4300 to 3100 ft. This result indicates that good maneuverability can be anticipated for high-speed hydrofoils fitted with supercavitating foils and blunt-based struts.

Under some conditions, it may be desirable to have much wider strut ventilation angles to allow for possible strut misalignment. The possibility of employing an active flow control by tangential blowing to suppress sudden side ventilation on base-vented struts of an 80-knot, 200-ton hydrofoil was examined by Rothblum,<sup>39</sup> with positive results. However, many assumptions advanced in this study require further verification.

#### CAVITY CONTROL STUDIES

If the cavity pressure on a supercavitating foil can be controlled, a high-speed hydrofoil should ride smoother in waves. Thus the sea-keeping quality of a hydrofoil can be evaluated in terms of cavity control.

Extensive studies on foil cavity pressure versus strut profiles on TAP-1 and TAP-2 systems were conducted at NASA<sup>23</sup> and Lockheed.<sup>33</sup> Full ventilation on both systems was observed when the TAP-1 parabolic struts were fitted with spray wedges. This approach (parabolic struts with spray wedges or pseudoblunt-based strut) provides a solution for the inability to achieve full natural ventilation of the foil cavity at high speeds.

Exploratory studies in calm water and waves to investigate the stability characteristics of foil cavity were conducted in the DTNSRDC towing tank by Conolly using two existing supercavitating foils and streamline struts. Significant findings were covered in a presentation by Wermter and Shen.<sup>20</sup> These experiments indicate that once the cavity

is vented to the free surface (see Figure 8), the flow on the foil is quite stable in calm water and waves. Further studies on cavity control of a supercavitating foil in waves were conducted by Stahl and Zarnick,<sup>27</sup> and the effectiveness of flaps for lift control was investigated in the water tunnel at California Institute of Technology.<sup>16</sup>

#### FLUTTER STUDIES

In the first fiscal year, efforts were made to identify important flutter parameters.<sup>18</sup> In the second fiscal year, a report was issued on design procedures and parametric trends that could be used to avoid flutter and divergence of hydrofoil strut/foil systems.<sup>29</sup> A fair amount of qualitative information on strut flutter characteristics has been generated. Hydrodynamic and structural parameters for T-foils on six full-scale naval hydrofoils have been investigated by Besch and discussed in Reference 20. Based on these results, a kinematically scaled strut flutter model (TAP flutter model) of a full-scale ventilated strut/pod/foil system was designed. The section profile of the strut is parabolic. The philosophy of this system design was discussed in Reference 40. The TAP flutter model is shown in Figure 9.

The TAP flutter model was first excited in water and in air to obtain vibration modes and frequency characteristics. An experiment was then conducted in the DTNSRDC high-speed towing tank by Besch. All model configurations tested were found to be stable throughout the speed range tested. Neither flutter (a dynamic instability) nor divergence (a static instability) was observed up to the highest test speed.

The scaling laws on prototype and model flutter speed have been developed by Besch and Liu.<sup>29</sup> According to this study, a strut for a 200-ton craft with a 66.5-in. chord and TAP flutter model configuration with attached propulsion pod would be stable to at least 110 knots (56.6 m/sec).<sup>40</sup> The theoretical calculation shows that a further improvement in the flutter speed can be anticipated if the propulsion pod is located at the junction of strut and foil.

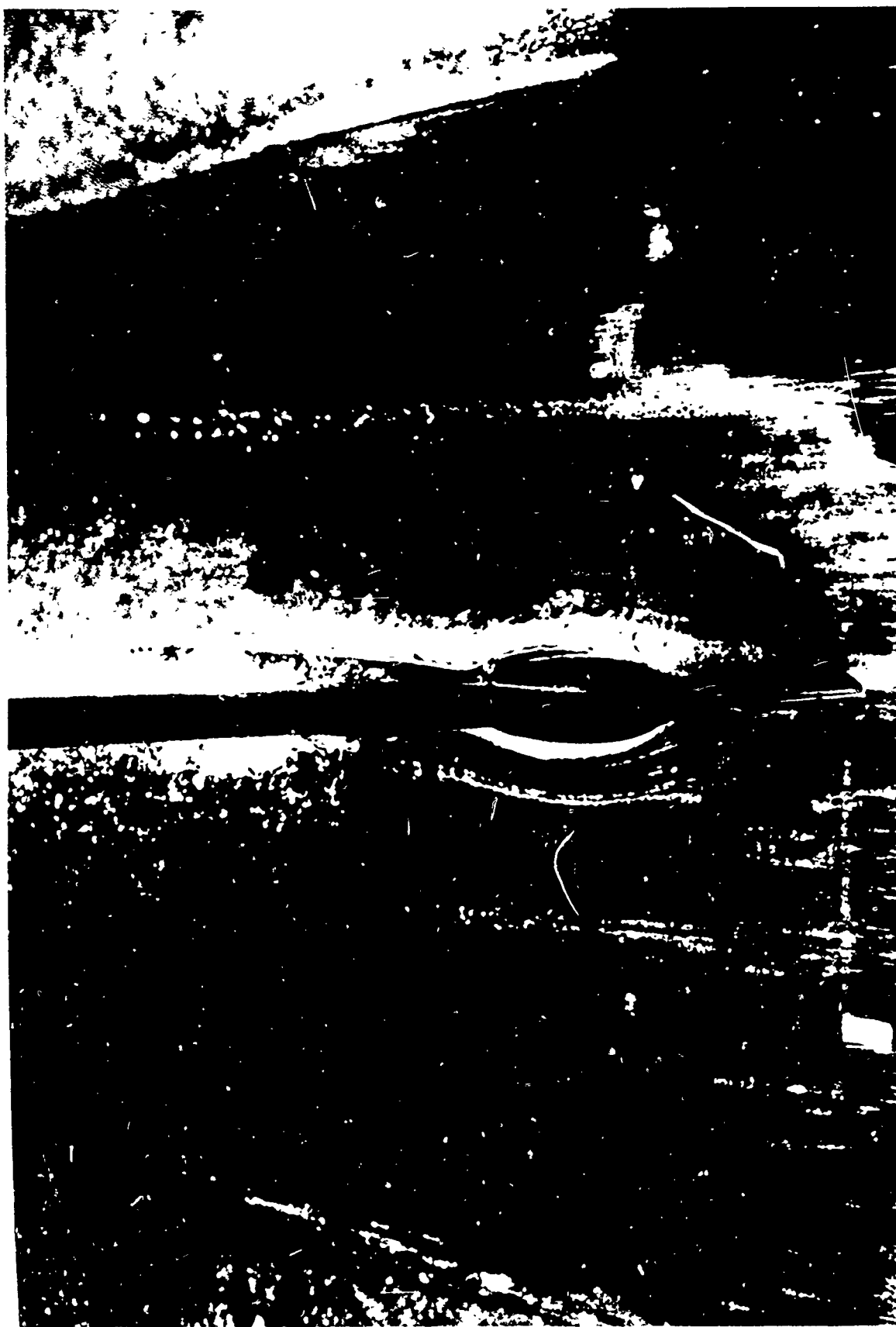


Figure 8 - Top View of Hydrofoil in a Superventilated Condition  
(in Waves)



Figure 9 - The TAP Hydrofoil Configuration Flutter Model



## OTHER CRITICAL AREAS

Because of fiscal limitations, some areas have been investigated only briefly: control devices to reduce lift, the flow boundaries of foil rewetting in waves, the effect of round noses on supercavitating flow performance, and smooth transition from subcavitating to supercavitating flow. Efforts in these areas should be continued in order to improve future foil designs.

## SUMMARY AND RECOMMENDATIONS

Representative hydrodynamic loads (critical loads) were established for high-speed strut/foil systems. Based on these critical loads, the feasibility of constructing the TAP-1 foil was investigated and verified. Designed with a conventional approach, this system was found to provide reasonable L/D ratios at high-speed operation. No vortex shedding or leading edge vibration was observed. However, takeoff with this system will be difficult.

A new strut/foil system (mixed foil and pseudoblunt-based strut) was subsequently introduced and developed as TAP-2. Theoretical studies on planoconvex foils and an experimental investigation of TAP-2 suggest that a mixed foil at moderate cruising speed can be designed to obtain hydrodynamic efficiency similar to that of existing hydrofoils. A reasonable range of foilborne operation can thus be anticipated. Takeoff with this new type of strut/foil system should pose no problems. A hydrofoil equipped with mixed foils offers the possibility of reasonably efficient operation at high speeds (above 50 knots) especially in rough seas. This cannot be done by hydrofoils equipped with existing airfoils.

The inability to achieve full natural ventilation on the foil cavity at high speeds has long been considered as a critical problem in the development of high-speed hydrofoils. A pseudoblunt-based strut and a parabolic strut with spray wedges are shown to be effective in providing full natural ventilation on the foil cavity at high speeds. These results are significant for cavity stability control on a supercavitating foil.

A set of data was generated on side force and ventilation characteristics of parabolic struts and the pseudoblunt-based strut. In a coordinated turn, a 200-ton hydrofoil at 80 knots can achieve turning rates of 4 to 5 deg/sec. Thus, good maneuvering characteristics of a high-speed hydrofoil can be anticipated.

A practical buildable strut of the TAP strut/pod/foil configuration had been developed. This strut was shown to be stable with respect to flutter and divergence at speeds up to at least 110 knots.

Inasmuch as the program resulted in the development of a strut/foil system capable of performing efficiently at moderate speeds with a reasonably good high-speed operational capability, it is recommended that a strut/foil system be designed and evaluated on a high-speed craft such as FRESH-1.

Other critical areas whose investigation was hampered by funding restrictions warrant future studies in the interest of improving foil efficiency.

#### ACKNOWLEDGMENTS

The work reported herein represents the combined efforts of many people, some of whom are cited in the references. Their dedication in carrying out specific tasks in support of the total project is acknowledged with appreciation.

Special thanks are also due to Dr. W. Morgan and to Messrs D. Cieslowski and G. Dobay for their helpful discussions and suggestions during the course of this work and to Miss C.W. Wright for administrative assistance throughout the project.

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**APPENDIX**  
**INFORMATION FOR SPONSOR**

TABLE 1 - EXPLORATORY STUDIES

	FY73	FY74	FY75
State-of-the-Art-Reviews	■		
Foil Section Studies	■		
Supercavitating Foil Studies			
Calm Water and Waves (DTNSRDC)	■		
Endplate Series (DTNSRDC)	■		
Flap Series (Cal Tech)	■	■	
Unsteady Cavity Flows (Penn State)	■	■	
Strut Ventilation Studies	■		
Dynamic Simulation Studies	■		
Other Special Studies	■		

TABLE 2 - REFINEMENT STUDIES

	FY73	FY74	FY75
TAP-1 Studies			
Design and Fabrication	■	■	
TAP-1 Strut/Foil Performance	■	■	
TAP-1 Strut Ventilation	■	■	
Scale Effect Studies		■	■
Development of Mixed Foil	■	■	
Cavity Control Studies in Waves	■	■	
Pseudo Blunt - Based Strut Studies	■	■	
Representative Hydrodynamic Loads	■	■	
Strut Flutter Studies	■	■	
Other Special Studies	■	■	

TABLE 3 - POTENTIAL CONCEPT VALIDATION

	FY73	FY74	FY75
TAP-2 Studies			
Design and Fabrication		■	■
TAP-2 Strut/Pod/Foil Performance		■	■
TAP-2 Strut Ventilation		■	■
Development of Design Theories	■	■	■
Structural Design Concept Validation	■	■	■
Flutter Model Validation	■	■	■
Dynamic Simulation Studies	■	■	■
Other Special Studies	■	■	■

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